Quark-gluon densities in the nuclear fragmentation region in heavy ion collisions at LHC

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Abstract. At the LHC, the leading partons in the nuclei are expected to interact with the maximal possible strength - black disk limit - up to transverse momenta of the order of few GeV. We demonstrate that in this limit the densities of the quark - gluon systems produced in the central AA collisions in the nucleus fragmentation regions should exceed $300GeV/fm^3$ which is at least as high as the densities discussed for the central region. Experimental signatures of such a regime are also discussed.

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The focus of most studies of the quark-gluon state produced in heavy ion collisions is the central region where one expects generation of high gluon densities at sufficiently high energies. The first estimates of the hadron matter densities produced in the nuclear fragmentation region were presented in [1] in the framework of the soft hadronic dynamics. The first estimate of the quark-gluon densities in this kinematics was presented within the framework of the onset of the black disk limit (BDL) of QCD in [2] which found densities at least a factor of ten larger. The purpose of this talk is review and update analysis the analysis of [2].

The starting point of [2] is the observation [3] that the transverse momenta of partons propagating through a high gluon density medium should become much larger than the scale of soft interactions. This is due to the possibility for a quark with given large x_1 to interact with partons with very small $x_2 = 4p_t^2/x_1 s$ where p_t is the resolution scale. As a result, for the case of a gluon with $x \geq 10^{-2}$ propagating through the center of the heavy nucleus we find an average of $p_t \geq 4GeV/c$ at the LHC energies, see review in [4].

Let us consider nucleus - nucleus scattering in the rest frame of one of the nuclei. First let us determine the emission angle, θ, of the parton belonging to the nucleus which was at rest. Since the energy losses are small, the light-cone fraction carried by the parton is approximately conserved:

$$(E_i - p_i^z) = xm_N, \tag{1}$$

leading to $p_z = (\mu^2 + p_t^2)/2xm_N - xm_N/2 \approx p_t^2/2xm_N$. Here in the last step we have neglected μ^2 compared to p_t^2 which is legitimate in the leading order. Since $\mu^2 \geq 0$, neglected terms would increase p_z making the emission angles, θ, even smaller. Thus, in the BDL the angles $\theta \simeq p_t/p_z \sim 2xm_N/p_t$ are small. So, the length of the produced wave package is reduced from the naive value of $2R_A$ by the large factor $S = 1/(1-\cos\theta) \approx p_t^2/2x^2m_N^2$.

However, we must also take into account that the products of the nucleon fragment as a whole move forward in the target rest frame. Since the knocked out partons carry practically the whole light cone fraction of the nucleon, the mass squared of the produced system, M^2 and its longitudinal momentum, p_z can be determined from $(\sqrt{M^2+p_z^2}-p_z)/m_N=1, M^2=\sum_i p_{i,\,t}^2/x_i$, where $x_i, p_{i,\,t}$ are light cone variables for produced partons. Hence, $p_z=M^2/2m_N$, and the Lorentz factor $\gamma=E/M=\sqrt{M^2+(M^2/2m_N)^2}/M\approx M/2m_N$. As a result we find the total reduction in the volume:

$$D=(2m_N/M)\cdot<p_t^2/2m_N^2x^2>. \tag{2}$$

Since the energy of the system in its rest frame is M, we find for the overall enhancement as compared to the nuclear density:

$$R_E=\frac{1}{N_q+N_g}\sum_i\frac{p_{it}^2}{m_N^2x_i^2}. \tag{3}$$

To illustrate the dependence of R_A on the total number of involved partons, N, and on average transverse momenta we can take all x_i and all p_{it}. In this case $D=Np_t/m_N, R_E=D^2$, and energy density depends quadratically on the average transverse momentum of partons.

Our estimates indicate that at LHC for the gluons with $x\geq 0.0.5$, $\left\langle p_{gt}^2\right\rangle\geq 16GeV^2$ (and growing with increase of x), and that for quarks $\left\langle p_{qt}^2\right\rangle$ is a factor of two smaller [4]. Taking for illustration $N_q=3, N_g=6, x_q=1/6, x_g=1/12$ and $\left\langle p_{gt}^2\right\rangle=20GeV^2$ we find $R_E=2300$. This corresponds to

$$\text{"}energy\ density\text{"}\sim 370\,GeV/fm^3,$$

which is at least as large as the one expected for the central region. It is much larger than our initial estimate where a very conservative value of $\left\langle p_{gt}^2\right\rangle$ was taken.

If we assume the proximity of BDL at RHIC for the fragmentation region for $p_t\sim 1GeV/c$, we find quark-gluon energy densities $\sim 10\,GeV/fm^3$. These densities are at least a factor of 10 higher than in [1] due to much larger release of energy in the BDL and due to significantly larger longitudinal compression of the interaction volume. Our estimate neglects the conversion of the released partons into hadrons before they reach the back edge of the fragmenting nucleus. If p_t generated in the collision is small enough, this effect may become important.

Using the logic similar to the one we used for estimating hadron formation in the color transparency phenomenon [5] we can estimate the distance over which a parton (not interacting with a medium) converts to hadrons. One finds

$$l_{coh}=2p_q/\Delta M^2 \tag{4}$$

where ΔM^2 is the mass gap between two lowest hadrons with the same quantum numbers. Numerically, $l_{coh}\approx 0.3\div 0.4\,fm\cdot p_q[GeV]$, corresponding for $p_q=4GeV$. This is substantially larger than the expected interaction length (see below) and hence the evolution of the imploded system should be determined mostly by partonic rather than hadronic interactions.

The difference in average x's of quarks and gluons leads to a different direction of the flow of the quarks and gluons in the center of mass frame of the produced system. For the above numerical example, $k_z/k_t \sim 0.7$ for quarks and ~ -0.25 for gluons. Obviously, this pattern will enhance the interactions of quarks and gluons at the next stage of the interactions, making equilibration more likely.

It follows from the above analysis that at LHC in the first stage of collisions a strongly compressed hot quark-gluon state of the ellipsoidal shape is formed with the small principal axis of $\sim 0.5\,fm$ and density $\rho \geq 50$ partons per fm^3. At the higher rapidity end, this ellipsoid boarders essentially parton free space; on the end close to central rapidities, it boarders a hot $q\bar{q}g$ state. The scattering length for parton i can be estimated as $l_i = 1/(\sum_j N_j \sigma_{ij})$, corresponding to the scattering length being smaller than 0.5 fm for $\sigma \geq 0.5 mb$. To estimate the interaction cross section, we note that the average invariant energy $s \approx 2p_t^2 \sim 32 GeV^2$. The initial stage of reinteractions certainly is a highly non-equilibrium process. Nevertheless to do a perturbative estimate we can conservatively introduce a cutoff on the momentum transfer $p \sim \frac{\pi}{2}\rho^{-1/3}$, leading to the leading order estimate for the gluon - gluon cross section $\geq 1 mb$. Nonperturbative effects, which remain strong in the gluon sector up to $s \sim 10$ GeV^2, are likely to increase these interactions further. Consequently, we expect partons to rescatter strongly at the second stage, though much more detailed modeling is required to find out whether the system may reach thermal equilibrium.

The large angle rescatterings of partons will lead to production of partons at higher rapidities and re-population of the cool region. In particular, two gluons have the right energies to produce, via gluon fusion $c\bar{c}, b\bar{b}$ pairs and in particular χ_c, χ_b-mesons with rather large transverse momenta and $x_F \sim 2x_g \sim 0.1$. Also, leading photons can be produced in the $qg \to \gamma q$ subprocesses, though in difference from the central region the $q\bar{q} \to \mu^+\mu^-$ production will be suppressed due to the lack of antiquarks. Another high density effect is the production of leading nucleons via recombination of quarks with subsequent escape to the cool region. Hence we expect a rather paradoxical situation that the production of leading hadrons in AA collisions will be stronger than in the central pA collisions.

To summarize, we have demonstrated that the onset of the BDL in the interactions in the target fragmentation region which is likely at LHC for a large range of virtualities, will lead to the formation of a new superdense initial state in the nuclear fragmentation region with densities exceeding nuclear densities at least by a factor of 2000. Our reasoning is however insufficient to demonstrate whether thermalization processes will be strong enough for the system to reach equilibrium necessary for formation of metastable states.

REFERENCES

1. R. Anishetty, P. Koehler and L. D. McLerran, Phys. Rev. D **22**, 2793 (1980).
2. L. Frankfurt and M. Strikman, Phys. Rev. Lett. **91**, 022301 (2003) [arXiv:nucl-th/0212094].
3. L. Frankfurt, V. Guzey, M. McDermott and M. Strikman, Phys. Rev. Lett. **87** (2001) 192301 [arXiv:hep-ph/0104154].
4. L. Frankfurt, M. Strikman and C. Weiss, Ann. Rev. Nucl. Part. Sci. **55** (2005) 403.
5. G. R. Farrar, H. Liu, L. L. Frankfurt and M. I. Strikman, Phys. Rev. Lett. **61**, 686 (1988).